Light hadron spectroscopy with $O(a)$ improved dynamical fermions.

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We present results for the hadron spectrum and static quark potential from a simulation with two flavours of $O(a)$ improved dynamical Wilson fermions at $\beta = 5.2$. We address the issues of sea quark dependence of observables and finite-size effects.

Quenching is the only non-systematically improvable approximation in lattice QCD. Moreover, sea-quark effects are to be taken into account if we are to make theoretical predictions on such phenomena as $\eta' - \pi$ splitting and string breaking. Dynamical simulations are computationally very expensive and control of systematic effects is thus of the utmost importance. The improvement counterterm $c_{\mathrm{SW}}(g_0^2)$ for the SW-improved action has been computed non-perturbatively, thus yielding full $O(a)$ improvement with $N_f = 2$ dynamical fermions [1].

The simulation parameters are summarized in tab. 1. For each volume and each value of κ_{sea} we have simulated valence quarks with an appropriate set of κ's to exploit the full $(\kappa_{\mathrm{sea}}, \kappa_{\mathrm{val}})$ plane for "strange" physics [2]. At $\beta = 5.2$ the PS/V mass ratios for the relevant κ's are shown in tab. 2. The value of c_{SW} used differs from the final estimate of the ALPHA Collaboration [1], but since a notable part of the simulation had already been carried out with this improvement coefficient, UKQCD have decided to continue the simulation, concentrating on finite-size effects and looking for signs of sea-quark effects in both the static quark potential and the light hadron spectrum. The complete removal of $O(a)$ artefacts is thus not the highest priority in this work. Details of the simulation and results can be found in [2], while we refer the reader to [3] for an up-to-date review on spectroscopy.

β	c_{SW}	$L^3 \cdot T$	κ_{sea}	Conf
5.2	1.76	$8^3 \cdot 24$	0.1370	78
			0.1380	100
			0.1390	100
			0.1395	60
5.2	1.76	$12^3 \cdot 24$	0.1370	151
			0.1380	151
			0.1390	151
			0.1395	121
			0.1398	98
5.2	1.76	$16^3 \cdot 24$	0.1390	90
			0.1395	100
			0.1398	69

Table 1
Simulation parameters.

1. Static quark potential

To set the lattice spacing, we have used the scale r_0 determined from [4]

$$F(r_0/a)(r_0/a)^2 = 1.65, \qquad r_0 = 0.49 \text{ fm}, \qquad (1)$$

where $F(r)$ is the force between two static quarks, derived from the potential $V(r)$, which is in turn extracted in a standard way from Wilson loops [2]. In Full QCD r_0 is better suited than the string tension, since the string is expected to break, and is also more reliable than the mass of the ρ, since it can decay. In fig. 1 we show r_0/a as function of $1/\kappa^{\mathrm{sea}}$ for the three volumes. Even though part of this strong dependence of a on κ_{sea} could be reabsorbed by improving the coupling [5], it indicates the necessity to work at a fixed scale, whenever possible [6]. Moreover, while comparing $8^3 \cdot 24$ and $12^3 \cdot 24$ there is a sizable difference at the lightest quark mass, the difference is completely negligible between $12^3 \cdot 24$ and $16^3 \cdot 24$. We can
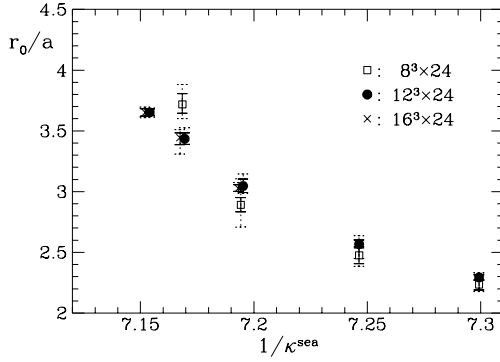
Figure 1. r_0/a as a function of $1/\kappa^{\mathrm{sea}}$. The solid errors are statistical and the dashed errors are systematic, as explained in [2].

summarise these results in a bound of $L/r_0 \gtrsim 3.2$ above which finite-size effects in the static quark potential are largely absent. Given the approximate linear behaviour of r_0/a at the three lightest quark masses, we have attempted a chiral extrapolation for the two largest volumes. In the chiral limit, we obtain $a = 0.121(2)$ fm and $a = 0.122(2)$ fm, for $12^3 \cdot 24$ and $16^3 \cdot 24$.

One can rescale the linear Coulomb ansatz of the potential

$$V(r) = V_0 + \sigma r - \frac{e}{r}, \qquad e = \pi/12, \qquad (2)$$

to eliminate σ as follows

$$[V(r) - V_0]r_0 = (1.65 - e)(r/r_0 - 1) - e(r_0/r - 1). \quad (3)$$

In fig. 2, we show the rescaled potential for $12^3 \cdot 24$ and for different values of κ^{sea}. The solid line doesn't represent a fit but simply a plot of eq. (3). In Full QCD, due to string breaking one expects the data to flatten out at large distances, below a value equal to twice the static meson mass. These limiting values have been calculated for $\kappa^{\mathrm{sea}} = 0.1390$ (dashes) and $\kappa^{\mathrm{sea}} = 0.1395$ (dots). With our present data, there is not conclusive evidence of string breaking up to $r \simeq 2.5 r_0$. A more chiral sea quark mass or a better way of extracting the potential are needed [2]. At small distances, the data seems well described by the Coulombian part even if the data for the lightest quark masses tend to lie somewhat below the curve. This seems to favour a value of $e > \pi/12$, as also observed in [7] for unimproved Wilson fermions. This is consistent with the influence of the dynamical quarks
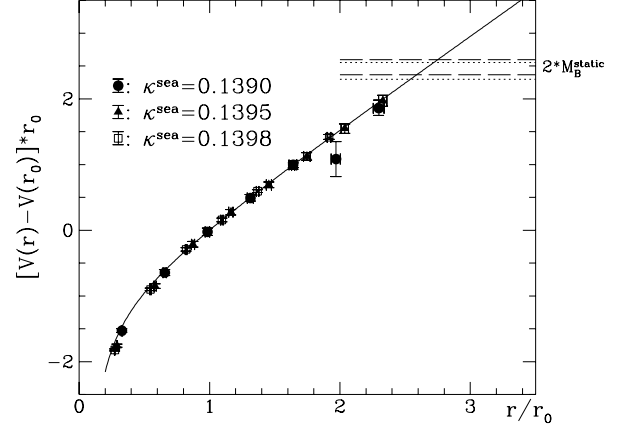

Figure 2. Rescaled potential at $V = 12^3 \cdot 24$ for the three lightest sea quark masses.

on the potential through the running of the strong coupling. We interpret this as a sign of unquenching and plan to carry out a quantitative analysis of the effect in a future publication, using the "correct" value of c_{sw} [6].

2. Light Spectrum

κ/Volume	$8^3 \cdot 24$	$12^3 \cdot 24$	$16^3 \cdot 24$
0.1370	$0.857 \, {}^{+\,6}_{-\,7}$	$0.855 \, {}^{+\,2}_{-\,3}$	
0.1380	$0.829 \, {}^{+\,9}_{-\,7}$	$0.825 \, {}^{+\,4}_{-\,5}$	
0.1390	$0.769 \, {}^{+\,10}_{-\,11}$	$0.785 \, {}^{+\,4}_{-\,7}$	$0.785 \, {}^{+\,6}_{-\,7}$
0.1395	$0.710 \, {}^{+\,16}_{-\,18}$	$0.710 \, {}^{+\,10}_{-\,10}$	$0.719 \, {}^{+\,7}_{-\,10}$
0.1398		$0.674 \, {}^{+\,9}_{-\,23}$	$0.670 \, {}^{+\,10}_{-\,13}$

Table 2
$m_{\mathrm{PS}}/m_{\mathrm{V}}$ ratios for the different volumes.

We have carried out a first complete analysis of the light hadron spectrum on the entire dataset, to gather complementary information to that obtained from the static quark potential. Amplitudes and masses have been obtained in a stardard way by correlated least-χ^2 fits to correlation functions. We have used throughout a double exponential fitting function, taking into account the backward propagating state for mesons. We have found that the influence of the first excited state is not negligible as we approach the most chiral point. In order to estimate the excitation, we have fitted simultaneously the correlator "fuzzed" both at sink and source, denoted FF, and the correlator with local sink and source, denoted LL.
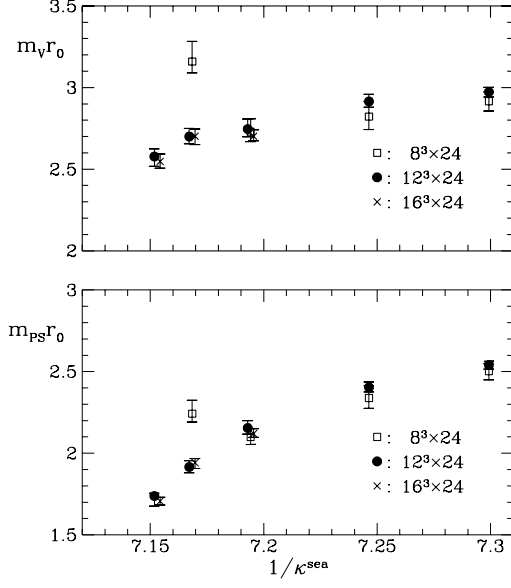
Figure 3. Meson masses for different volumes, in units of r_0.

Figure 4. Vector vs pseudoscalar squared, in units of r_0, for $V = 12^3 \cdot 24$ at three values of κ^{sea} and comparison with quenched ($\kappa^{\mathrm{sea}} = 0$).

The FF correlator allows a much faster isolation of the fundamental state than the LL correlator.

In fig. 3 we show the vector and pseudoscalar mesons, as a function of $1/\kappa^{\mathrm{sea}}$, calculated at $\kappa^{\mathrm{val}} = \kappa^{\mathrm{sea}}$ for the different volumes. To allow a significant comparison, we report all masses in units of r_0, which reabsorbs the dependence of the lattice spacing on κ^{sea}. The plots show pronounced finite-size effects between $8^3 \cdot 24$ and $12^3 \cdot 24$ as we move towards the most chiral point. On the other hand, between $12^3 \cdot 24$ and $16^3 \cdot 24$ we find no significant discrepancy within statistical accuracy at all values of the quark mass. A qualitatively similar picture is bourne out of the baryon sector. This behaviour confirms the one found for the static quark potential and we can extend to the mass spectrum the bound for finite-size effects of $Lr_0 \gtrsim 3.2$ already found there.

One way to investigate sea quark effects in the spectrum is through the parameter J [8], which only requires the input of a physical V/PS mass ratio. In Full QCD, we need to fix κ^{sea} and vary the valence quark mass, interpreted as having strange flavour in a sea of light quarks. However, our most chiral sea quark mass is only in the strange region. Moreover, the errors are amplified by the fitting process to extract the dm_V/dm_{PS}^2 slope, especially at the lightest mass. In view
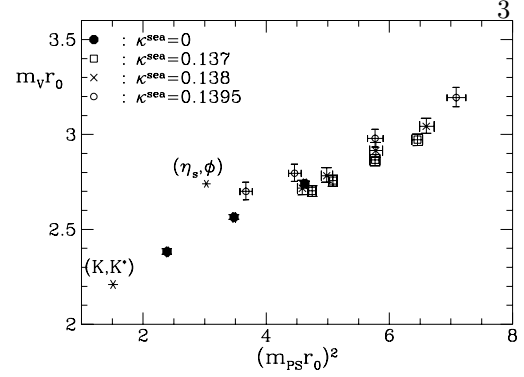
of all this, it is not surprising that the values of J show no appreciable trend towards the experimental value as the sea quark mass decreases, as shown in ref. [2]. Another way to look for dynamical effects, equivalent in spirit but which bypasses any fitting procedure, is to look at the (m_V, m_{PS}^2) plane directly for a shift in the data, calculated at fixed κ^{sea} and different κ^{val}, as we approach the chiral limit. In fig. 4 we show such a plot and also report the quenched result for comparison ($\kappa^{\mathrm{sea}} = 0$), calculated at $\beta = 5.7$ and $V = 12^3 \cdot 24$, which has a comparable lattice spacing. As the sea quark mass decreases, we do observe a significant, albeit small, trend towards the point $(m_{\eta_s}^2, m_\phi)$, i.e. the mesons whose flavour content resembles most closely that used in our simulation. Moreover, at the lightest sea quark mass, we can assert a significant shift compared to the quenched result. To quantify this quenching effect, we do need to keep the scale constant, an issue which will be addressed with the fully $O(a)$ improved action [6].

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